Transient dynamics of the moving meniscus

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Microfluidic schemes exploiting electromechanical forces such as electrowetting-on-dielectric (EWOD) and dielectrophoresis (DEP) combine high speed with geometric simplicity and voltage-based control. While the hydrostatic behavior of these devices has been studied extensively, the dynamics have received far less attention. Particularly important is the strongly-coupled interfacial behavior of the moving contact line. This behavior encompasses the contact angle and the profile of the moving interface, interfacial vibrations due to AC voltage, and a frictional, dynamic “line force” that impedes forward displacement of the liquid.

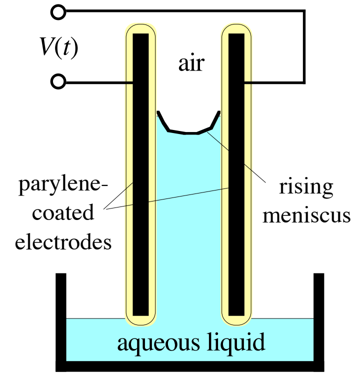

Fig.1. Modified Pellat experiment using dielectrically coated electrodes to study dynamics of rising meniscus.

In the past, we used Pellat’s experimental geometry to observe time-dependent height-of-rise as a function of voltage, electrode spacing, and frequency [1]. Se Fig. 1. We are now investigating the transient behavior of the rising liquid column, using a high-speed camera to record meniscus shape, contact angle, and contact line velocity. The experiments cover voltages from 25 to 150 V-rms at frequencies between 100 Hz and 100 kHz. Videos recorded at 1000 fps are adequate to capture the important dynamics. Individual frames were processed with a MATLAB™ program to obtain quantitative data such as contact angle and other features of the moving meniscus.

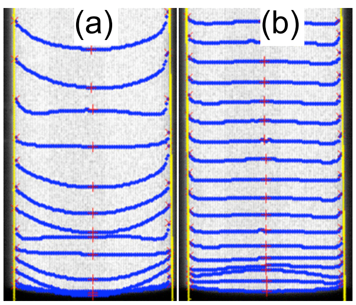

Fig. 2. Profiles of rising meniscus at 1 ms intervals from captured videos taken between electrodes. Spacing = 0.5 mm. Voltage =150 V-rms. (a) 100 Hz. (b) 100 kHz.

The videos reveal transient behavior comprised of a superposition upon the electromechanically-driven upward liquid displacement of complex, time-dependent motion of the rising liquid surface. In the frequency regime << 20 kHz, where electrowetting rules and the electric field is concentrated in the dielectric layer, the contact angle rapidly decreases and the meniscus takes on a concave profile within ~1 ms after voltage is applied. When the liquid bulk starts moving, the contact angle increases and the meniscus flattens, in some cases even bulging upward. This oscillation of the meniscus between concave and convex profiles, with corresponding fluctuations of the contact angle, continues as the liquid column rises. Fig. 2a shows superimposed meniscus profiles recorded at 1 ms intervals.

At frequencies >> 20 kHz, in the DEP regime where the electric field penetrates the liquid, center-of-mass motion precedes contact line changes, so that the meniscus becomes convex in the first few milliseconds. After ~3 ms, the contact line starts to move upward, and the contact angle decreases while the meniscus flattens somewhat. The upward motion then proceeds with a roughly unchanged, slightly convex meniscus profile. This behavior is recorded by a sequence of profiles, again recorded at 1 ms intervals, in Fig. 2b. Near 20 kHz, the dynamic profile exhibits behavior that is intermediate between the high and low frequency limits just described.

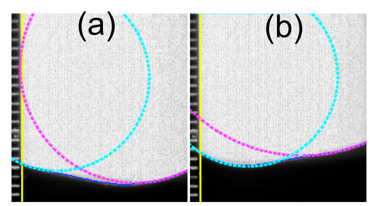

Fig. 3. Liquid meniscus exhibiting sloshing motion. Electrode spacing = 2 mm. Voltage = 150 V-rms at 100 Hz. (a) time = 16 ms (b) time = 21 ms after actuation. Cyan and magenta curves are best-fit circles used to estimate contact angles at left and right sides, respectively.

Another interfacial effect, observed only at frequencies below ~ 500 Hz is a back-and-forth sloshing motion of the meniscus. This resonant motion, at twice the frequency of the applied voltage, is believed to the manifestation of a parametric interfacial instability, presumably limited in amplitude by some non-linear mechanism. Fig. 3 shows this sloshing motion at two time-adjacent extrema of the sloshing motion. The liquid contact angles at the left and right electrodes, measured using a best-fit circle routine, are (a) t = 16 ms: q_{left} = 67.6°, q_{right} = 62.4° and (b) t = 21 ms: q_{left} = 61.7°, q_{right} = 68.8°.

We observe voltage-related limits on the dynamic height-of-rise related to contact angle saturation. It is possible that the sloshing motions and the upward transient motion itself may influence time delayed onset of saturation reported in earlier experiments [1].

References

[1] K.-L. Wang and T. B. Jones, “Electrowetting dynamics of microfluidic actuation”, Langmuir, vol. 21, pp. 4211-4217, 2005.

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